Stemflow and its controlling factors in the subshrub *Artemisia ordosica* during two contrasting growth stages in the Mu Us sandy land of northern China

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ABSTRACT

The yield of stemflow from vegetation is mostly affected by rainfall and canopy structure, but few past studies have paid attention to the dynamics of canopy structure during the growth season. *Artemisia ordosica* is a typical subshrub, very different from trees and shrubs. Assessing the influence of canopy structure and rainfall on stemflow yield in *A. ordosica* during the growth season will fill a knowledge gap in our understanding of stemflow yield from subshrub species. This study therefore examined the effects of those two factors on stemflow at two growth stages of *A. ordosica*, using 20 experimental individuals in the Mu Us sandy land of northern China. It demonstrated that the mean stemflow percentage of gross rainfall (SF%) for this subshrub was 8.56%, and the average funneling ratio was 75.80. The critical control factors of stemflow volumes were rainfall amount and canopy area, which varied greatly during the growth season. The SF% was significantly lower during the reproductive growth stage than during the vegetative growth stage, because of the rapid increase in leaf area index at the former stage. This evaluation of the effects of vegetation growth dynamics on stemflow yield will improve the accuracy of future hydrological models.

Key words | canopy structure, rainfall, stemflow yield, vegetation dynamics

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INTRODUCTION

Stemflow is defined as water that drains along the exterior of plant branches and boles from rain or snowmelt (Levia *et al.* 2015). Stemflow plays an important ecohydrological and biogeochemical role in vegetated ecosystems, because it is a spatially localized point input of water and nutrients at the plant stem (reviewed by Levia & Frost 2003). Stemflow generally represents less than 10% of the amount of gross rainfall, and it is always considered as a minor component of forest canopy water budgets, compared with interception and throughfall (Li *et al.* 2008b; Levia *et al.* 2015). As a result stemflow receives minor attention, making it underrepresented in the literature (Llorens & Domingo 2007).

Previous studies on stemflow have been conducted primarily in tropical and temperate forests, with relatively few studies having documented the stemflow characteristics for shrubs in semi-arid and arid regions (Carlyle-Moses 2004; Li *et al.* 2008b). Stemflow can be concentrated and stored in deeper soil layers, so it represents an important potential source of available moisture for shrub growth in desert ecosystems, where water is scarce (Tromble 1987; Li *et al.* 2008b, 2009). The existing studies on shrub stemflow were mainly focused on deciduous shrubs, but rarely on subshrubs, which are characterized by a woody, perennial base with annual, herbaceous shoots.

Stemflow shows great variability among and within types of vegetation (Levia & Frost 2003; Li 2011). Llorens & Domingo (2007) reported that stemflow averaged 3% of gross rainfall under Mediterranean conditions, but with a 111% coefficient

of variation. Numerous previous studies have indicated that stemflow yield is influenced by both abiotic and biotic factors. The abiotic factors include rainfall (amount, intensity and duration) (e.g. Levia & Frost 2003; Li *et al.* 2008b; Yang *et al.* 2008) and wind (Van Stan *et al.* 2011). The main biotic factors are vegetation species, plant age, canopy height, canopy area, basal area, branch angle, leaf area index (LAI), bark roughness, biomass, presence of leaves, and epiphyte coverage (e.g. Navar & Bryan 1990; Martinez-Meza & Whitford 1996; Crockford & Richardson 2000; Levia & Frost 2003; Garcia-Estringana *et al.* 2010; Zhang *et al.* 2015). In fact, many abiotic and biotic factors are mutually interactive, such that actual stemflow yield – at the level of species and individuals – results from a complex and dynamic set of interactions that cascade as a function of space and time (Levia *et al.* 2015).

Canopy structure is a key factor that accounts for differences in stemflow yield (Crockford & Richardson 2000; Levia & Frost 2003; Li *et al.* 2008b). However, the elements of canopy structure change substantially during growing seasons, so it is difficult to obtain some canopy structure metrics during growth (e.g. total leaf count, canopy area, leaf area, and biomass) (Levia *et al.* 2015). Canopy structure parameters were traditionally assumed to be static constants in the hydrologic model (Zimmermann *et al.* 2015), and hence they were measured using destructive sampling methods in past experimental studies. Knowledge gaps therefore persist, regarding the effects of vegetation growth dynamics on stemflow production.

To address those gaps, the objectives of this study were to: (1) determine the influence of rainfall characteristics (amount and intensity) and canopy structure (basal diameter, canopy area, leaf area, LAI and individual height) on stemflow yield for the unstudied subshrub *Artemisia ordosica*; and (2) compare stemflow yield processes between two contrasting growth stages (vegetative growth stage versus reproductive growth stage).

MATERIALS AND METHODS

Study site

The field experiment was conducted at the Ordos Sandland Ecological Research Station, Chinese Academy of Sciences,

during the rainy season from May to September in 2012. The station is located at the northeastern margin of the Mu Us Sandland in the Inner Mongolia Ordos plateau (39° 29′ 37.6″ N, 110° 11′ 29.4″ E) at an elevation of approximately 1,300 m. The climate is continental semi-arid. Mean annual precipitation is 345 mm, occurring mainly between July and September, and mean annual pan evaporation is 2,535 mm. Mean annual temperature is 8 °C with a maximum monthly temperature of 22 °C (July) and a minimum of −10 °C (January). The landscape is mainly fixed dunes and mobile dunes with aeolian sandy soil (Zhang 1994). The dominant plant species in the study area is *Artemisia ordosica*, and prevalent associated species include *Hedysarum mongolicum*, *Poa attenuata* spp., *Cleistogenes squarrosa*, *Oxytropis psammocharis* and *Cynanchum komarovii* (Zhang *et al.* 2007).

A. ordosica, a medicinal and sand-binding subshrub of the Asteraceae, is distributed widely across northern and northwestern China (Li *et al.* 2008a). Mature individuals are 0.6–1.0 m tall, with numerous slender branches extending from the base of the main trunk; the above-ground part of the subshrub is approximately hemispherical from the center. Compared to deciduous shrubs, subshrubs like this species have high guard cell compliance and more potential hydraulic conductance due to their less lignified stems and leaves (Gao *et al.* 2013). The individuals sampled for experiments were situated in an area where grazing is prohibited, near the meteorological observation station.

Experimental setup

It was difficult to accurately measure canopy structure metrics (e.g. leaf area) on live plants with indirect estimation methods during the growth period, because the leaf of *A. ordosica* is very small, and morphology of the canopy is dynamic and complex during different growth stages (Figure 1). We therefore selected 20 individuals and divided them into two groups based on similar morphological characteristics, in order to enable direct destructive measurements at two different growth stages (Table 1). Stage A was measured during the vegetative growth stage from 28 May to 22 July, using 10 individuals with a gradient of basal diameter. Stage B included the other 10 individuals, also across a gradient of basal diameter, which were measured during the reproductive growth stage from 23

Figure 1 │ (a) *Artemisia ordosica* subshrub; and (b) stemflow collection apparatus on trunk of an experimental individual.

July to 16 September. At the end of each growth stage, the study individuals were excavated and leaves were clipped from the branches. Leaf area was measured by the scan method: the test samples were scanned as black-and-white patterns at 600 dpi, and the leaf area (black pixels) was counted using MATLAB software (MathWorks, Inc. 2008). The LAI was calculated as the quotient of leaf area and the canopy area. Other canopy structure parameters including basal diameter, canopy area and shrub height were also measured. Basal diameter was measured as collar girth at the trunk base. Canopy area was measured by taking the east–west and north–south diameters through the center of the fullest part of the canopy, and then calculating the elliptical area. Shrub height was measured at the center of the canopy.

An aluminum foil cylinder was fitted around the stem of each individual and secured with silicone sealant to collect stemflow (Bui & Box 1992) (Figure 1). Stemflow drainage from each sample was funneled into a plastic bottle via a flexible rubber hose, and measured with a graduated cylinder immediately after each rainfall event. The stemflow volume (mL) of each plant was divided by its canopy area to calculate the stemflow depth (mm) of each *A. ordosica* individual. Rainfall was measured automatically and recorded at

Table 1 │ Canopy structure characteristics of the experimental *A. ordosica* individuals for Stage A and Stage B

Stage A					Stage B				
No.	*BD mm	CA cm²	LA cm²	H cm	No.	BD mm	CA cm²	LA cm²	H cm
A1	3.14	39.25	35.99	39.0	B1	3.58	63.59	104.87	50.0
A2	4.42	169.56	52.68	42.0	B2	4.10	241.78	209.35	52.0
A3	4.57	155.43	52.14	36.0	B3	5.45	296.73	213.02	53.0
A4	5.30	153.86	56.18	38.0	B4	7.86	314.00	330.95	50.0
A5	7.91	263.76	88.08	51.0	B5	11.00	1,577.85	607.38	62.0
A6	8.15	596.60	92.71	51.0	B6	13.94	2,763.20	948.06	61.0
A7	11.50	923.16	158.55	57.0	B7	16.68	2,899.88	1,238.46	88.0
A8	12.22	1,130.40	238.95	77.0	B8	17.06	2,731.80	862.42	71.0
A9	21.46	955.28	391.01	58.0	B9	24.86	3,689.50	1,229.41	72.0
A10	33.95	1,610.82	836.39	57.0	B10	35.11	3,626.70	1,940.43	66.0
Mean	11.26	599.81	200.27	50.6	Mean	13.96	1,820.50	769.44	62.5
±SD	9.62	531.58	249.42	12.5	±SD	10.03	1,485.83	589.43	12.2

*BD = basal diameter, CA = canopy area, LA = leaf area, H = subshrub height, SD = standard deviation.

10 min interval with a tipping bucket rain gauge (Delta-T, Cambridge, UK) located in an open area 10 m away from the study plots. Average rainfall intensity (I, mm/h) was used to represent rain intensity. The minimum rainfall (rainfall thresholds) for stemflow generation was estimated by linear regression equations between individual stemflow and individual rainfall (Diskin 1970; Li *et al.* 2008a, 2008b). The stemflow percentage of gross rainfall (SF%) was calculated by dividing rainfall amount (mm) by stemflow depth (mm) based on individual rainfall events.

Stemflow funneling ratio, *F*, was calculated using the following equation:

$$F = \mathrm{SF}_V / (BA \times P) \tag{1}$$

where SF_V is stemflow volume (L), BA is trunk basal area (m²), and P is the amount equivalent of gross incident precipitation (mm) (Herwitz 1986). The product $BA \times P$ provides the volume of water that would have been caught by a rain gauge with an opening equal to that of the trunk basal area. Thus, *F* represents the ratio of the amount of precipitation delivered to the base of the shrub to the rainfall that would have reached the ground if the shrubs were not present. A funneling ratio >1 indicates that canopy components other than the trunk are contributing to stemflow (Herwitz 1986; Carlyle-Moses & Price 2006; Li *et al.* 2008b).

Levene's test and *t*-test were used to analyze differences in rainfall regime and canopy structure between Stage A and B. A significant Levene's test ($P < 0.05$) means that equal variances were not assumed (Schultz 1985), and the results of the *t*-test are meaningful. Correlations between the stemflow volume and canopy structure variables were assessed using Pearson's correlation analysis. All statistical tests were performed using SPSS for Windows Version 13.0 (SPSS Inc., Chicago, USA).

RESULTS

Characteristics of rainfall and canopy structures

A total of 45 rainfall events were recorded from 28 May to 16 September in 2012, with a total amount of 520.6 mm.

Only 23 of them had an amount large enough (>1.0 mm) to enable observation of the yield of stemflow. Some erroneous data were discarded, such as measures of stemflow that exceeded the volume of the collection container because of extreme rainfall. Then, 16 typical rainfall events were chosen for analysis, accounting for 43.5% of the total amount of rainfall and 37.7% of the total number of rainfall events during the growing season. Half of the rainfall events (N = 8) occurred during the vegetative growth stage, with a range from 1.2 to 26.2 mm. Similarly, eight rainfall events occurred during the reproductive growth stage, with a range from 2.2 to 30.8 mm. The rainfall intensities (I, mm/h) ranged from 0.4 to 11.7. There is no significant difference in either the amount or intensity of rainfall between the two growth stages, based on t-test comparisons of Stage A and Stage B (Table 2).

The detailed characteristics of canopy structure of all 20 sampled individuals are shown in Table 1, and differences between the canopy structures of the two growth stages are shown in Table 2. There were significant differences in leaf area (*t*-test, $P = 0.011$) and canopy area (*t*-test, $P = 0.030$) between Stage A and Stage B, but not in basal diameter (*t*-test, $P = 0.542$) or subshrub height (Levene's test, $P = 0.981$). There are positive linear relationships between canopy area and base diameter in both growth stages, but the slope of the line was significantly larger in the reproductive growth stage (Figure 2). Another distinct difference was observed for LAI, which was almost 1.8 times higher in the reproductive growth stage.
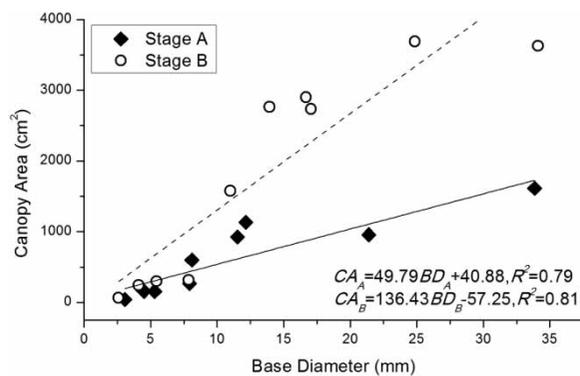
Relationships between stemflow and rainfall characteristics and canopy structures

Among the 16 analyzed rainfall events, 20% of the samples started to generate stemflow when rainfall reached 1.2 mm, while all of them generated stemflow when rainfall was over 4.4 mm. This suggested that the minimum rainfall for stemflow yield was about 1.2–4.4 mm for *A. ordosica*. The stemflow percentage of gross rainfall (SF%) averaged 8.56% (range 1.39–18.51%), which reflected a large coefficient of variation. The mean funneling ratio was 75.80, which also showed much variation with a range of 11.50–135.98. There is a
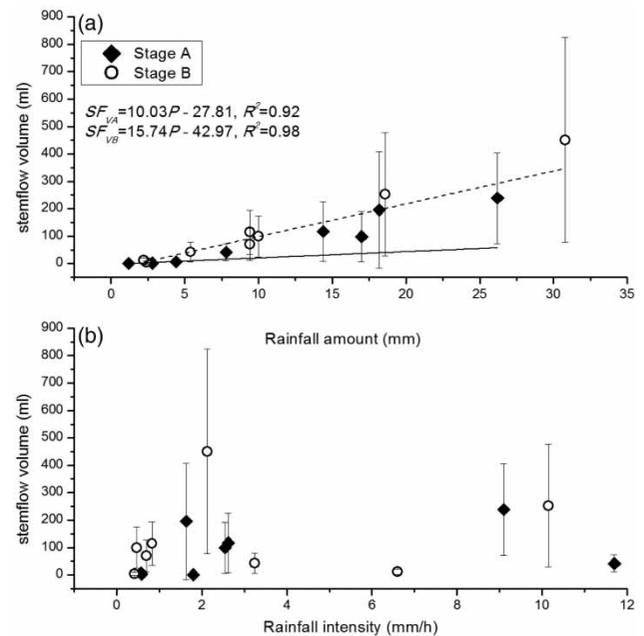
Table 2 | Results of Levene's test and *t*-test for comparison of the influencing factors of rainfall characteristics (rainfall amount and intensity) and canopy structure (canopy area, base diameter, leaf area, height, and LAI) for stemflow volume between Stage A and Stage B

	Stage	Mean	Std deviation	Levene's test		*t*-test	
				F	Sig.	T	Sig. (2-tailed)
Rainfall amount (mm)	A	10.78	8.54	0.005	0.942	0.057	0.955
	B	10.52	9.72				
Rainfall intensity (mm/h)	A	3.60	3.97	0.089	0.769	0.293	0.773
	B	3.07	3.54				
Canopy area (cm^2)	A	599.81	531.58	26.175	0.000*	− 2.483	0.030*
	B	1,820.50	1,485.83				
Base diameter (mm)	A	11.26	9.62	0.073	0.790	− 0.622	0.542
	B	13.96	10.03				
Leaf area (cm^2)	A	200.27	249.42	7.239	0.015*	− 2.827	0.011*
	B	770.44	586.95				
Height (cm)	A	50.6	12.5	0.001	0.981	− 2.151	0.045*
	B	62.5	12.2				
LAI (cm^2/cm^2)	A	0.37	0.22	3.691	0.071	− 1.901	0.073
	B	0.66	0.43				

*Correlation is significant at the 0.05 level.

Figure 2 | Linear relationships between canopy area (*CA*) and base diameter (*BD*) for the vegetative (Stage A) and reproductive (Stage B) growth stage.

Figure 3 | Relationships between stemflow volume (*SF*) and (a) rainfall amount (*P*) and (b) rainfall intensity (*I*) for the vegetative (Stage A) and reproductive (Stage B) growth stage.

strong linear correlation between stemflow and rainfall (Figure 3(a)), but not between stemflow and rainfall intensity (Figure 3(b)). A regression of stemflow volume (SF_v) against the amount (*P*) and intensity (*I*) of rainfall ($SFv = 10.17P\text{-}0.83I\text{-}26.31$, $R^2 = 0.93$) demonstrated that stemflow was governed more by rainfall amount than by intensity (Figure 3). There are strong linear correlations between stemflow volume and canopy area (Figure 4(a)), base diameter (Figure 4(b)), and leaf area (Figure 4(c)) for both of the growth stages, while subshrub height is not correlated with stemflow.

Effect of growth stages on stemflow yield

There are exponential relationships between SF%, funneling ratio and rainfall amount (Figure 5). The mean SF% is
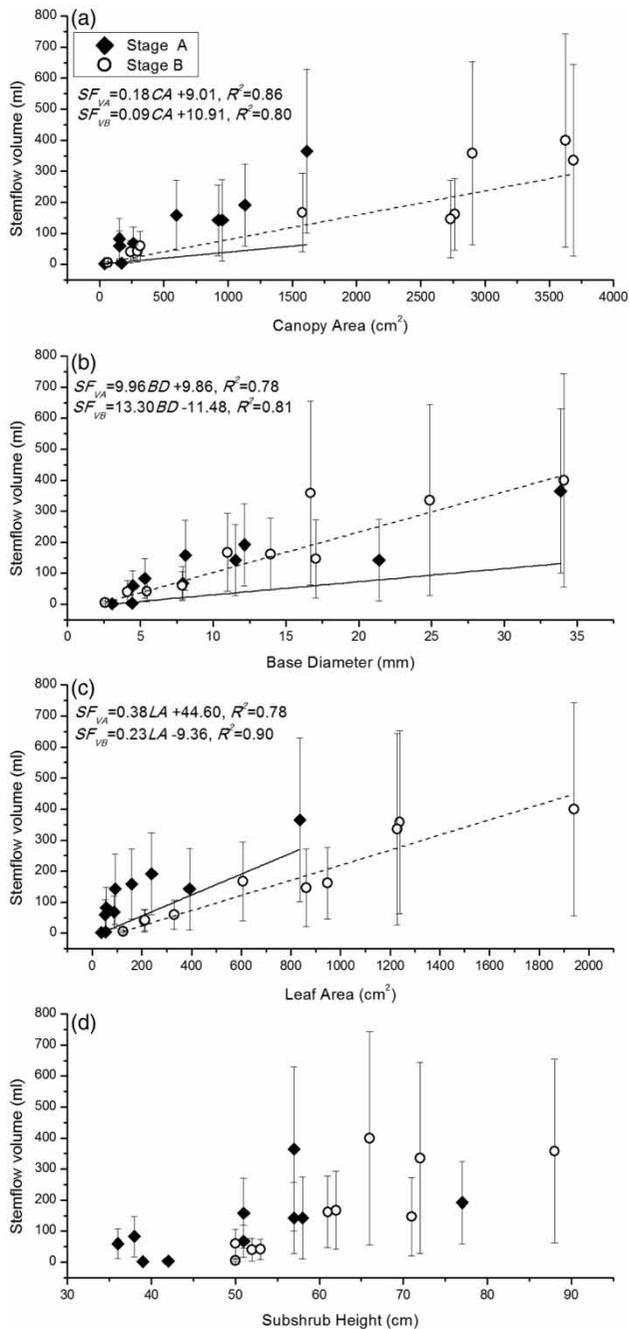
Figure 4 | Relationships between stemflow volume (SF) and (a) canopy area (CA), (b) basal diameter (BD), (c) leaf area (LA), and (d) subshrub height (H) for the vegetative (Stage A) and reproductive (Stage B) growth stage.
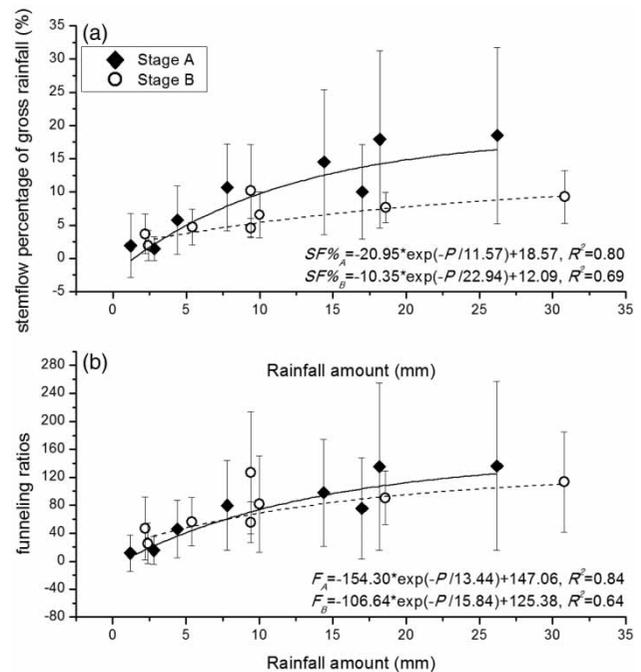

Figure 5 | Relationships between rainfall amount (P) with (a) stemflow percentage (SF%) and (b) funneling ratios (F) for the vegetative (Stage A) and reproductive (Stage B) growth stage.

10.39% in the vegetative growth stage (range 1.39–18.51%) and 6.50% in the reproductive growth stage (range 1.95–10.19%). The latter value is significantly less than the former (t-test, P = 0.01) with a lower coefficient of variation (Figure 5(a)). However, there is no significant difference in the average funneling ratio (t-test, P = 0.85), which is 76.83 (range 11.50–135.98) and 74.64 (range 25.37–126.56) in the two growth stages, respectively (Figure 5(b)). The predicted rainfall thresholds determined by linear regression (Figure 4(a)) were 2.45 for Group A and 2.73 mm for Group B, values that matched well with the observed rainfall thresholds.

Mean stemflow for each sample in the two stages is shown in Figure 6, with the basal diameters of samples increasing from sample nos 1 through 10. Larger plants tended to generate more stemflow volume under the same rainfall conditions (Figure 6(a)); however, SF% was greater in medium-sized plants (Figure 6(b)), which is consistent with the rules of funneling ratios (Figure 6(c)).

Stemflow volume is significantly and positively correlated with rainfall amount, basal diameter, canopy area and leaf area in both growth stages (Table 3). However, there is a significant negative correlation between stemflow volume and LAI in only the reproductive stage (Table 3). This suggests that LAI has different impact on stemflow yield at different growth stages, which could be important for stemflow modeling.
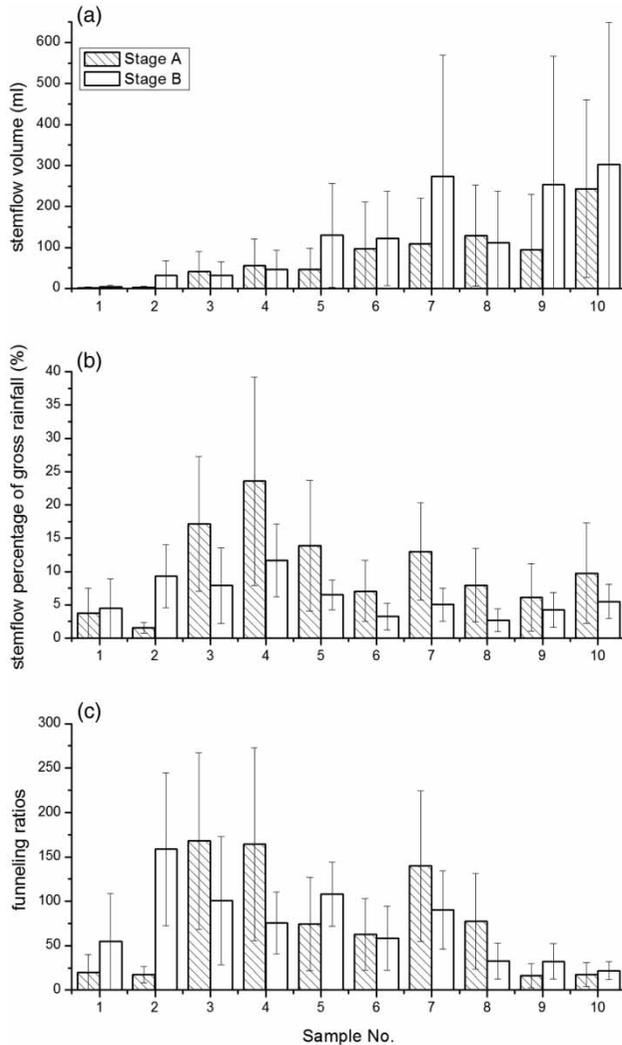
Figure 6 │ Stemflow characteristics of the experimental *A. ordosica* individuals for the vegetative (Stage A) and reproductive (Stage B) growth stage: (a) average stemflow volume; (b) stemflow percentage; and (c) funneling ratio. The Sample No. refers to Table 1, and the samples are ordered by increasing basal diameter.

DISCUSSION

The findings of this study demonstrate that rainfall amount, canopy area and leaf area are the critical factors that govern stemflow yield of the subshrub of *A. ordosica* (Table 3). The positive linear relationship between stemflow volume and rainfall for *A. ordosica* in this study agrees well with that for shrub species reported by previous studies (Price & Carlyle-Moses 2003; Li *et al.* 2008b; Yang *et al.* 2008; Janeau *et al.* 2015). It is interesting to note that the greater the size of the *A. ordosica*, the more stemflow volume it produces (Figure 6(a)), but the medium-sized individuals tend to generate more stemflow per unit canopy area (SF%, Figure 6(b)) and direct more rainfall to the base of the plant (funneling ratio, Figure 6(c)) than either small- or large-size individuals. The possible reason is that the ratio of woody to foliar biomass is greater for medium-sized individuals than that of small- or large-size individuals.

Levia *et al.* (2015) reported that stemflow yield was large for trees with greater ratio of woody to foliar biomass. Average funneling ratio is 75.8 for *A. ordosica*, meaning that the canopy of the *A. ordosica* subshrub can collect 75.8 times the amount of water that rainfall delivers to the plant's base as a point input resource (Janeau *et al.* 2015). Thus, branches and stems were contributing fully to stemflow yield because the funneling ratios were larger than 1 (Navar 1993). The ratio in the study is higher than values reported for other shrub species, such as *Artemisia sphaerocephala* (41.5, Yang *et al.* 2008), *Salix psammophila* (69.4, Yang *et al.* 2008), *Tamarix ramosissima* (24.8, Li *et al.* 2008b) and *Reaumuria soongorica* (53.2, Li *et al.* 2008b), but lower than the ratio for *Caragana korshinskii* (153.5, Li *et al.* 2008b). The stemflow

Table 3 │ Pearson correlation coefficients between stemflow volume and rainfall and canopy structure characteristics for Stage A and Stage B

	P mm	I mm/h	BD mm	CA cm²	LA cm²	H cm	LAI cm²/cm²
SF$_{VA}$ (mL)	0.964**	0.227	0.897**	0.944**	0.893**	0.630	−0.196
SF$_{VB}$ (mL)	0.993**	0.192	0.904**	0.904**	0.952**	0.820**	−0.638*

SF$_{VA}$ = mean stemflow volume of Stage A, SF$_{VB}$ = mean stemflow volumes of Stage B, P = rainfall amount, I = rainfall intensity, BD = basal diameter, CA = canopy area, LA = leaf area, H = individual height, LAI = leaf area index.
*Correlation is significant at the 0.05 level.
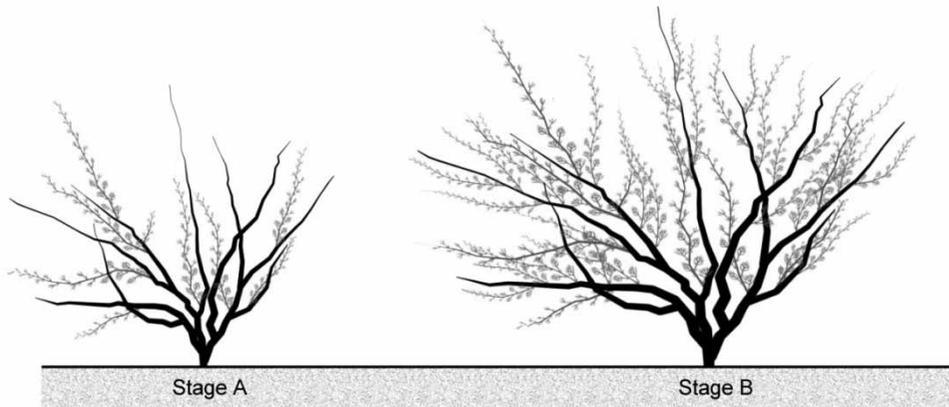**Correlation is significant at the 0.01 level.

Figure 7 | Conceptual diagram of canopy architecture for *A. ordosica* subshrub in the vegetative (Stage A) and reproductive (Stage B) growth stage.

percentage and funneling ratio of *A. ordosica* (SF% = 8.56%, F = 75.80) were comparable with values for *S. psammophila* (SF% = 7.6%, F = 69.4; Yang *et al.* 2008), another common sand-fixed shrub in China.

This study also highlights the importance of plant canopy dynamics in stemflow yield. Significant differences in leaf area and canopy area were found between vegetative (Stage A) and reproductive (Stage B) growth stages of *A. ordosica*, which in turn resulted in different responses to stemflow production. The stemflow volume of Stage B was significantly greater than that of Stage A, because the former has greater leaf area and canopy area. However the stemflow percentage, which was based on per unit projected canopy area, was much greater for Stage A (Figure 6). The contrasting stemflow behavior between the two growth stages is attributed to the unique trait of canopy structure during growth for the subshrub species, which has two distinct kinds of branches: vegetative shoots are perennial and ligneous, whereas reproductive shoots are annual and herbaceous (Feng *et al.* 2009). During the reproductive stage, many twigs with tender leaves are sent forth from the primary branches, and they tend to expand laterally (Figure 7). Lower SF% for the reproductive stage than the vegetative stage may be explained by the following:

- More leaves rather than woody branches grow in the reproductive stage, more woody biomass in the vegetative stage will produce larger stemflow (Levia *et al.* 2015).
- Many leaves shelter branches and favor canopy interception in the reproductive stage. The rapid increase of LAI

in the reproductive stage accounts for an increase in canopy storage capacity, which will lead to greater canopy interception of rainfall (Herwitz 1985; Dunkerley 2000; Llorens & Gallart 2000).
- Lateral canopy architecture and low secondary branch angles relative to the ground reduce the transmission of water to the woody surface and hence decrease stemflow percentage in reproductive growth stage.

This study reveals that the unique growth pattern creates a significant difference in the canopy structure characteristics of the two growth stages of *A. ordosica*, and consequently the stemflow also differs greatly at those times of the year. Since canopy structure is dynamic and complicated for certain vegetation types, further studies are needed to investigate the effect of dynamic canopy structure on stemflow production for a wide range of vegetation species, which would be a challenging step in advancing understanding of the effect of canopy on the hydrology and biogeochemistry.

CONCLUSION

The factors that control stemflow yield for the subshrub *A. ordosica* at two typical growth stages were evaluated in this study. The results advance our understanding of the effects of growth dynamics on stemflow yield. The growth pattern of subshrubs in a semi-arid area differed greatly from those of trees and shrubs, which in turn had important

influences on canopy structure and stemflow yield. The stemflow yield was influenced not only by rainfall events, but also by individual canopy structure characteristics. Large plants generated more stemflow volume, especially during large rainfall events; however, medium-sized plants tended to direct more rainfall to their bases per unit canopy area. Overall, the major control factors of stemflow volumes were rainfall amount and canopy area, which were not constant, but varied throughout the growth seasons. Hence, discrimination of different growth stages will be helpful for improving the accuracy of eco-hydrology model simulations to assess the water dynamics of subshrubs in semi-arid regions. The results of this work fill a knowledge gap in our understanding of stemflow production for sub-shrub species.

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